THE PROMPT ULTRAVIOLET/SOFT X-RAY EMISSION OF GRBs

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Abstract. We discuss the prompt emission of gamma-ray bursts (GRBs), allowing for $\gamma\gamma$ pair production and synchrotron self-absorption. The observed hard spectra suggest heavy pair-loading in GRBs. The re-emission of the generated pairs results in the energy transmission from high-energy gamma-rays to long-wavelength radiation. Due to strong self-absorption, the synchrotron radiation by pairs is in optically thick regime. Thus, the re-emission would appear as a thermal-like spectral bump in the extreme-ultraviolet/soft X-ray band, other than the peak from the main burst. The confirmation of the thermal-like feature and the double-peak structure by future satellites, such as *Swift*, would indicate that the dominant radiation mechanism in GRBs is synchrotron rather than inverse-Compton radiation.

Keywords: gamma-rays: bursts, radiation mechanisms: nonthermal, relativity

1. Introduction

In the past few years, a standard model of gamma-ray burst (GRB) afterglows was well established, in which the ambient medium of GRBs are shock-heated by relativistic expanding blast-waves and give rise to synchrotron/inverse-Compton (IC) emission (Mészáros, 2002). However, the prompt emission of GRBs is believed to be irrelevant to ambient medium, and its radiation mechanism is still poorly known so far.

The recent definite proof of GRB 030329 associated with a type Ib/c supernova confirmed, as long suspected, that GRBs, at least the long class, originate from explosions of massive stars in distant galaxies (Stanek et al., 2003; Hjorth et al., 2003). Since GRBs are events occurring on stars, the emission region may be compact, and the huge energy release will lead to the formation of $e^{\pm}$, γ fireballs, exhibiting thermal-like spectra. But the GRB spectra are non-thermal and hard, with a significant fraction of the energy above the $e^{\pm}$ pair formation energy threshold. For a photon with tens of MeV to escape freely, avoiding $\gamma\gamma$ interactions, the fireball must be ultra-relativistic expanding, with $\Gamma \gtrsim 100$ (Lithwick and Sari, 2001, and references therein). The afterglow studies has also confirmed the presence of ultra-relativistic motion. However, if the intrinsic emission, before leaking out from fireball, includes radiation with even higher energy, say, beyond GeV, these radiation still suffers $\gamma\gamma$ absorption, leading to pair loading in GRBs. In the context of relativistic fireball model, Li et al. (2003, hereafter L03) found that, in a wide range

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of model parameters, the resulting pairs may dominate those electrons associated with fireball baryons. The presence of abundant pairs would affect the behaviors of the early afterglow from reverse shocks (L03), and may also emit particular signals in the bursting phase.

We discuss here the prompt GRB emission, with emphasis on the re-emission by the secondary $e^{\pm}$ pairs. If the energy density in the emission region is dominated by magnetic field, the pairs would re-emit mainly by synchrotron radiation, rather than IC process (e.g., Pilla and Loeb, 1998). Due to strong self-absorption, the pair emission appears as a thermal-like bump in the GRB spectrum. (Fan and Wei, 2004 have also studied the pair emission, but with less stress on the self-absorption effect.) This is of significant interest, since the detection of this feature would infer that synchrotron mechanism plays a dominant role in GRBs.

2. Pair Loading in GRB Fireballs

Let us consider a GRB central engine that produces a relativistic wind outflow, with an isotropic energy E, a bulk Lorentz factor Γ and a width Δ. We assume the isotropic geometry, which is valid even for a jetted GRB as long as the Lorentz factor $\Gamma > 1/\theta_{\rm jet}$, with $\theta_{\rm jet}$ the jet opening angle. The energy carried in the outflow may be composed of two components, the bulk kinetic energy of baryons (E_k) and the energy of magnetic field (E_B). The ratio between them can be defined as $\sigma \equiv E_B/E_k$ (e.g., Zhang and Mészáros, 2002). These energies are carried from the central engine to some radius R where GRB emission arises. As in L03, the emission site can be constrained by the non-thermal spectra and rapid varying light curves of GRBs, leading to typical value of $R \sim 10^{14}$ cm for $\Gamma \sim 300$. The width of outflow is $\Delta \lesssim 10^{12}$ cm for a wind lasting for a duration of $T \lesssim 100$ s. Thus the emission region can be usually regarded as a thin shell, with $\Delta \ll R$.

In the kinetic-energy dominated model, i.e., $\sigma < 1$, the bulk kinetic energy is dissipated by internal shock waves within the unsteady outflow, where the magnetic field strength B is in the equipartition value $B \sim (8\pi U_\gamma)^{1/2} = 10^4 L_{\gamma,51}^{1/2} \Gamma_{300}^{-1} R_{14}^{-1}$ G, with $L_\gamma = 10^{51} L_{\gamma,51}$ ergs s^{-1} the GRB luminosity, $\Gamma_{300} = \Gamma/300$ and $R_{14} = R/10^{14}$ cm. Here the equipartition mean the energy stored in the magnetic field, protons and electrons (and hence the released radiation) are comparable. In the magnetic-energy dominated model, the magnetic field strength could be much larger than the above equipartition value. Thus, we here assume that in general the radiation-to-magnetic energy ratio in emission region is $Y \equiv U_\gamma/U_B < 1$, and the magnetic field is scaled as $B = 10^4 B_4$ G in the following.

Due to the large luminosity and hard spectrum of a GRB, any intrinsic high energy gamma-rays produced in the GRB emission region could be absorbed for pair production. As in L03, the cut-off energy, above which the photons suffer strong absorption, and the number of produced pairs can be estimated from the observed GRB spectra. The observed photon spectra of GRBs can be approximated by a broken power-law, with a high-energy portion of the form $dN_\gamma/d\epsilon \propto \epsilon^{-\beta}$ for $\epsilon > \epsilon_{\rm p}$, where $\epsilon_{\rm p} \sim m_e c^2$ is the energy at the broken point and the index $\beta \sim 2$–3. The number of the produced secondary pairs is equal to the absorbed photons above $\epsilon_{\rm cut}$. Assuming the intrinsic spectrum above $\epsilon_{\rm cut}$ follows the same power law below $\epsilon_{\rm cut}$, we calculate the pair number as $N_\pm = N_\gamma(>\epsilon_{\rm cut}) \simeq (E_\gamma/\epsilon_{\rm p})(\epsilon_{\rm cut}/\epsilon_{\rm p})^{-(\beta-1)}$. Since the timescale of $\gamma\gamma$ collisions (comoving frame), $t'_{\gamma\gamma} \simeq [(\sigma_T/5)n'_\gamma c]^{-1} = 0.2\Gamma_{300}R_{14}^2 L_{\gamma,51}^{-1}$ s, is usually shorter than the dynamic time (comoving frame), $t'_{\rm dyn} \simeq R/\Gamma c = 10 R_{14}\Gamma_{300}^{-1}$ s, the resulting pairs remain inside the outflow.

As in L03, $\epsilon_{\rm cut}$ should be defined by the photon energy at which the optical depth for $\gamma\gamma$ absorption equals unity, $\tau_{\gamma\gamma}(\epsilon) = 1$, where the optical depth can be given by a simplified expression under the thin-shell assumption of the emission region, $\tau_{\gamma\gamma}(\epsilon) = (11/180)\sigma_T N_\gamma(>\epsilon)/4\pi R^2$ (Lithwick and Sari, 2001). Furthermore, the observed cutoff energy must be larger than $\Gamma m_e c^2$. Therefore, we obtain

$$\epsilon_{\rm cut} = \max\left[0.3\left(\frac{R_{14}^2}{E_{\gamma,52}\epsilon_0^{\beta-2}}\right)^{1/(\beta-1)}\Gamma_{300}^2;\quad 0.2\Gamma_{300}\right]\mathrm{GeV}, \tag{1}$$

where $\epsilon_0 = \epsilon_{\rm p}/m_e c^2$, and hereinafter the numerical coefficient corresponds to $\beta = 2.4$. It can be seen that the detection of the cutoff energy can help to constrain the parameters Γ and R. EGRET had ever detected prompt GeV emission in several GRBs, without obvious attenuation (e.g., GRB 930131; Sommer et al., 1994). We expect that the future satellite *GLAST*, which works at the energy range from 10 MeV up to more than 300 GeV, could observe such a cutoff at multi-GeV.[1] With $\epsilon_{\rm GeV} = \epsilon_{\rm cut}/1$ GeV, the pair number is written as

$$N_\pm \simeq 3\times 10^{53} E_{\gamma,52}\epsilon_{\rm GeV}^{-(\beta-1)}\epsilon_0^{\beta-2}. \tag{2}$$

For comparison, the number of baryonic electrons in the fireball is $N_{\rm b} = E/(1+\sigma)\Gamma m_{\rm p}c^2 = 2\times 10^{52}E_{52}\Gamma_{300}^{-1}(1+\sigma)^{-1}$, with $E_{52} = E/10^{52}$ ergs. So pairs become the dominant component. The baryonic electrons are expected to be responsible for the prompt hard X-ray emission, whilst the pairs may give rise to low energy emission, discussed in the following section.

3. Extreme-Ultraviolet Bump in the Prompt Emission

The initial energy distribution of the generated pairs follows the form of the photon spectrum, i.e., $dn_\pm/d\gamma_e \propto \gamma_e^{-\beta}$ for $\gamma_e > \gamma_\pm$, where $\gamma_\pm$ corresponds to the cutoff energy, $\gamma_\pm = \epsilon_{\rm cut}/2\Gamma m_e c^2 \simeq 3.3\epsilon_{\rm GeV}\Gamma_{300}^{-1}$. These pairs will cool down by synchrotron rather than IC radiation in the $Y \lesssim 1$ condition here. Because of the strong magnetic field in the emission region, the synchrotron-cooling timescale of pairs, $t'_{\rm syn} = 8B_4^{-2}\gamma_\pm^{-1}$ s, is shorter than the fireball dynamical time, implying that the pairs are always fast cooling. We show later that the pair annihilation time scale is shorter than the system dynamical time and also than the pair-cooling timescale, so pair annihilation is negligible.

For these fast cooling pairs, their energies are emitted quickly. As a result, the energy above $\epsilon_{\rm cut}$ in the intrinsic spectrum re-arises as the pair emission. The luminosity of the pair emission is given by

$$L_{\pm} \simeq \frac{\beta-1}{\beta-2}\frac{N_{\pm}\epsilon_{\rm cut}}{T} \simeq 2\times10^{50} L_{\gamma,51}\left(\frac{\epsilon_0}{\epsilon_{\rm GeV}}\right)^{\beta-2} {\rm ergs\, s^{-1}}, \quad (3)$$

with $L_\gamma = E_\gamma/T = 10^{51} L_{\gamma,51}$ ergs s^{-1} the GRB luminosity, and the characteristic synchrotron frequency is

$$\nu_{\pm} = 0.9\times10^{14}\Gamma_{300}^{-1}\epsilon_{\rm GeV}^{2} B_4 {\rm Hz}. \quad (4)$$

If we assume $Y \ll 1$, the synchrotron radiation plays a dominant role of pair cooling, rather than IC process. In this condition, the luminosity $L_\pm$ will peak at frequency $\nu_\pm$. Thus a very intense optical flash will emerge accompanying the prompt gamma-rays if neglecting the self-absorption. However, as shown in the following, the self-absorption is strong in such low energy range, with the absorption frequency $\nu_{\rm a} \gg \nu_\pm$, i.e., most of the pair emission occurs in the optically thick regime. Similar to the case of reverse flash in the condition of $\nu_{\rm c} < \nu_{\rm m} < \nu_{\rm a}$, which is discussed by Kobayashi et al. (2004), a thermal-like bump will arise in the low energy range of a GRB spectrum.

The self-absorption suppresses the emission below absorption frequency $\nu_{\rm a}$, and the suppressed emission energy is redistributed again among the pairs, preventing the pairs cool down immediately. So, the pairs and the radiation obtain a mechanism to exchange their energies. The final result is that the initial injected pair energy is redistributed among pairs and radiation, leading to a bump in the spectrum. The emission in the hard X-ray band is not in the optically thick regime, and is not involved in the energy redistribution. In the GRB duration T, the pair energy is radiated around $\nu_{\rm a}$, where the flux is given by $F_{\nu_{\rm a}} \simeq L_\pm/4\pi D_L^2\nu_{\rm a}$, with D_L the GRB luminosity distance. We follow the simple way by Sari and Piran (1999) to estimate the maximal flux as a blackbody with the pair temperature, $F_{\nu_{\rm a},{\rm bb}} \approx \pi(R_\perp/D_L)^2(2\nu_{\rm a}^2/c^2)kT_\pm$, where $R_\perp \simeq R/\Gamma$ is the observed size of the fireball, the pair temperature is $kT_\pm \simeq \Gamma\gamma_a m_e c^2/3$, and γ_a is the pair Lorentz factor that corresponds to $\nu_{\rm a}$ and is given by $(2\pi m_e c\nu_{\rm a}/\Gamma eB)^{1/2}$. Equating $F_{\nu_{\rm a},{\rm bb}} \simeq F_{\nu_{\rm a}}$ yields the self-absorption frequency

$$\nu_{\rm a} \simeq 1\times10^{16} L_{\pm,50}^{2/7}\Gamma_{300}^{3/7}R_{14}^{-4/7}B_4^{1/7}{\rm Hz}, \quad (5)$$

which is in the extreme-ultraviolet (EUV) band in the source frame. Since $\nu_{\rm a} \gg \nu_\pm$, most of the emission is absorbed and re-distributed, giving rise to a black-body like bump in the GRB spectrum, with peak frequency around $\nu_{\rm a}$ (Eq. 5) and luminosity $L_\pm$ (Eq. 3).

Notice that $\nu_{\rm a}$ is insensitive to all the parameters (Eq. 5), and would be fixed in the 10–100 eV range (in source frame) for various GRBs. However, Gou et al. (2004) had pointed out that between the Lyman-α frequency corresponding to the source frame and $\sim$0.2 keV, the GRB flux will be strongly subject to intergalactic and galactic absorption. Hence only the optical/UV or soft X-ray emission is expected for observation. Below $\nu_{\rm a}$ the spectrum behaves as $F_{\nu<\nu_{\rm a}} = F_{\nu_{\rm a}}(\nu/\nu_{\rm a})^2$, then the observed pair emission at 1 eV is

$$F_\nu^{\rm ob}(1\,{\rm eV}) \simeq 0.9 \frac{L_{\gamma,51}(1+z)^3}{D_{28}^2 \nu_{a,16}^3} \left(\frac{\epsilon_0}{\epsilon_{\rm GeV}}\right)^{\beta-2} {\rm mJy}, \tag{6}$$

where $\nu_{a,16} = \nu_{\rm a}/10^{16}$ Hz, and we have obviously shown the dependence on redshift z. Whereas in the band above $\nu_{\rm a}$, the emission is in optically thin regime and still exhibits the form radiated by the initial pairs, $F_{\nu>\nu_{\rm a}} = F_{\nu_\pm}(\nu/\nu_\pm)^{-\beta/2}$, where $F_{\nu_\pm} \simeq L_\pm/4\pi D_L^2 \nu_\pm$. If observed at 1 keV, the flux contributed by pairs is then

$$F_\nu^{\rm ob}(1\,{\rm keV}) \simeq 3 \times 10^{-8} \frac{L_{\gamma,51}}{D_{28}^2} \left[\frac{\epsilon_0^2 B_4}{\Gamma_{300}(1+z)}\right]^{(\beta-2)/2} {\rm ergs\,cm^{-2}s^{-1}keV^{-1}}. \tag{7}$$

This calculation is valid until at a high enough frequency where the emission is dominated by the main peak of the GRB. These prompt optical/UV and X-ray emission are expected to be observed by the UVOT and XRT detectors, respectively, on board the up-coming *Swift* satellite.

Finally, we estimate the annihilation rate of $e^\pm$ pairs. The comoving-frame annihilation timescale of the pairs in the thermal-like bump, with the comoving-frame temperature $\gamma_{\rm a} m_{\rm e} c^2$, is $t'_{\rm ann} \simeq (\sigma_{\rm ann} n_\pm c)^{-1}$, where $\sigma_{\rm ann} \simeq (3\sigma_T/8\gamma_{\rm a})(\ln 2\gamma_{\rm a} - 1)$ is the annihilation cross section, and the pair number density is given by $n_\pm \approx n_\gamma(>\epsilon_{\rm cut}) \simeq L_\pm/4\pi R^2 \Gamma c \epsilon_{\rm cut}$. In the calculation here, the baryonic electrons are neglected. The annihilation fraction of pairs, $f_{\rm ann}$, can be estimated by $t'^{-1}_{\rm ann}$ times the comoving-frame dynamical timescale $t'_{\rm dyn}$, $f_{\rm ann} \sim 0.08(L_{\pm,51}/\Gamma_{300}^3 R_{14})(10/\gamma_\pm\gamma_a)$. Since $f_{\rm ann} \ll 1$, most produced pairs will survive from annihilations and, as suggested by L03, be carried into the reverse shock later on, leading to a pair-rich reverse flash peaking at wavelengths longer than the optical band.

Though some pairs really annihilate into photons with energy $\epsilon_{\rm line} \simeq \Gamma\gamma_{\rm a} m_{\rm e} c^2$, no line feature would appear in the GRB spectrum. If $\epsilon_{\rm line} > \epsilon_{\rm cut}$, the photons would turn into pairs again. Otherwise, since the line luminosity $L_{\rm line} \sim f_{\rm ann} L_\pm < L_\pm \sim L_\gamma(>\epsilon_{\rm cut}) < L_\gamma(>\epsilon_{\rm line})$, the line flux is too low to stick out from the high-energy spectrum of the GRB.

As a result, the intrinsic high-energy emission in the GRB spectrum is absorbed and then transferred to a thermal-like bump in the EUV band, as shown in Figure 1.

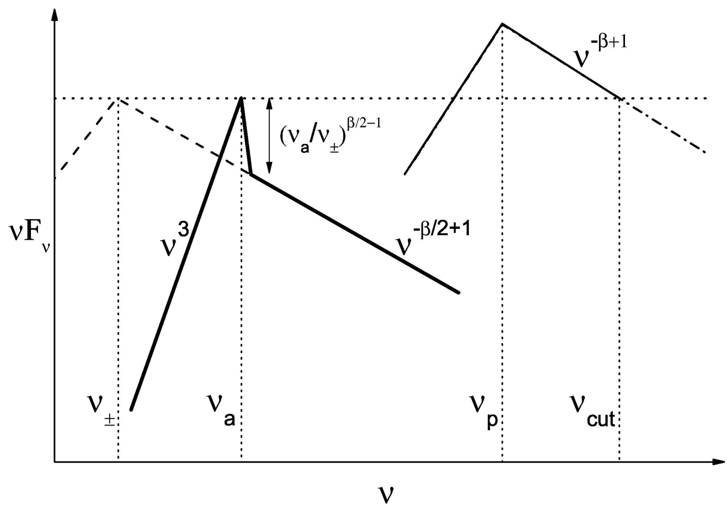

Figure 1. The schematic diagram of the νF_ν spectrum of the GRB prompt emission. Note that $\nu_p = \epsilon_p/h$ and $\nu_{cut} = \epsilon_{cut}/h$. The *thin solid* line shows the GRB emission with cutoff above ν_{cut} due to $\gamma\gamma$ pair production, while the *dashed-dotted* line is the intrinsic spectrum without cutoff. The synchrotron radiation by the resulting pairs is shown by the *thick solid* or *dashed* lines, corresponding to with or without self-absorption, respectively. The maximum around ν_a would appear as a thermal-like peak.

Since these features are expected to arise if $Y \ll 1$, the observation would provide a constraint on the magnetization parameter and the radiation mechanism in GRBs.

4. Summary and Discussion on Observation

We study the prompt GRB emission, taking into account the $\gamma\gamma$ pair production and synchrotron self-absorption. In context of relativistic fireball model, and based on the observed characteristics of GRB emission, we find that the resulting pairs usually dominate the baryonic electrons. The pairs will give rise to further emission by synchrotron radiation in the strong magnetic field, which is also responsible for the prompt hard X-ray emission. However, the pair emission occurs in the optically thick regime due to strong self-absorption, leading to a thermal-like spectral bump in the extreme UV/soft X-ray band, other than the peak in the hard X-ray band. The pair annihilation rate is estimated to be negligible, and hence no obvious annihilation lines appear in GRBs.

Some primary hypotheses have been taken in our calculation. First, we assume that the emission region is transparent for Compton scattering, even though the secondary pairs increase significantly the total optical depth. For typical parameter values this assumption is protected. However, if X-ray flashes (XRFs) are optically thick due to pair formation, as suggested by Mészáros et al. (2002), our calculation using Eq. (2) may underestimate the pair-loading in XRFs, which may need detailed works of numerical simulation. Secondly, we assume strong magnetic field, $Y < 1$, in the emission region. If $Y > 1$, the pairs lose most energy by IC scattering the GRB photons, and the IC photons are not self-absorbed again since beyond the optically thick regime, hence no effective energy exchange between pairs and photons is established and the bump disappears. Therefore, once UV/soft X-ray bumps are detected this will infer $Y < 1$ and that it is synchrotron rather than IC radiation that gives rise to the sub-MeV emission of GRBs.

After a GRB, the subsequent fireball-medium interaction will also lead to very early emission in UV/optical band due to a reverse shock sweeping up the fireball material, which may confuse the observation. However, the reverse-shock emission is different in their spectral shape, with the α-slope ($F_\nu \propto \nu^\alpha$) order of ($5/2, \sim -1/2$) or ($1/3, \sim -1/2$) for pair-rich or pair-poor reverse shock, respectively (L03). Comparing with $\alpha \sim 2$ for pair emission in UV/optical band, this can be easily distinguished by observation.

It is further discussed in Li and Song (2004) that the recent observation of a dust halo around GRB 031203, which infers a spectral peak of the prompt burst emission in the soft X-ray band, seems to be consistent with the predicted double-peak structure. The peak of the bump is always subject to strong absorption, but we can diagnose it by the spectral slopes in the the UV/Optical and soft X-ray band. It is of particular interest that for high-redshift GRBs, from Eq. (6) and $D_L(z) \propto (1+z)[1 - 1.25/(1+z)^{1/2}]$ for $z \gtrsim 3$ (analytical fits of Pen 1999, with $\Omega_{\rm tot} = 1$ and $\Omega_{\rm m} = 0.3$), the UV flux scales with z faster than $\propto (1+z)$. Therefore UVOT may even be encouraged to detect the prompt emission from high-z GRBs.

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Note

1. Though the cosmic infrared background can also absorb high energy gamma-rays from cosmological GRBs, this external attenuation affects only gamma-rays higher than hundreds of GeV (e.g., Salamon and Stecker, 1998).

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